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Commercial Frequency Linear Induction Motor Propulsion System

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COMMERCIAL FREQUENCY LINEAR INDUCTION MOTOR PROPULSION SYSTEM

by

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Kingston, Ontario

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17. Résumé

Ce rapport rend compte des travaux d'analyse conceptuelle d'un système de propulsion par moteur linéaire à fréquence fixe et à réglage de la vitesse par variation de la tension d'alimentation. Il présente les performances théoriques du moteur étudiées sur ordinateur et traite de certaines considérations pouvant influencer le rapport performances/coût. Il explique les objectifs visés, les contraintes en jeu ainsi que les matériels requis pour réaliser un prototype, et fait le bilan comparatif du système préconisé par rapport à un système à fréquence variable, dans le cas du transport hectométrique aéroportuaire. De plus, il renferme les données de calcul du moteur, les spécifications relatives à la commande ainsi que des devis estimatifs concernant celle-ci et obtenus des fabricants. Le rapport conclut essentiellement qu'il n'y a pas lieu d'engager des capitaux et des recherches supplémentaires vu les faibles avantages offerts par le moteur linéaire à inducation à fréquence industrielle, pour l'application envisagée, c'est-à-dire le transport hectométrique aéroportuaire.

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1.0 DESIGN OBJECTIVES

It is intended to design, build and test a propulsion system which would extend the current knowledge concerning:

1. Fixed-frequency (60 Hz) control of Linear Induction Motors (LIM's).

2. Use of solid-steel (no aluminum top-cap) reaction rail.

The prototype propulsion system will be sized so as to be representative of a "real" application, e.g., Airport People-Mover (APM).

The motor design will be based on the Intermediate Capacity Transit System (ICTS) LIM concept insofar as mechanical topology and thermal limits are similar, however the winding design, reaction-rail design and power-conditioning will have differences arising from the fixed-frequency concept.

The primary motivation behind the proposed development program is to investigate the "low cost" potential of a fixed frequency LIM system. Section 6 of this report indicates where the important cost/performance trade-off areas are. Section 8 provides a cost comparison estimate which attempts to isolate the factors which have the greatest bearing on overall system cost.

2.0 DESIGN CONSTRAINTS

2.1 MECHANICAL CONSTRAINTS

The mechanical dimensions of the LIM core will be identical to the ICTS LIM. (The intention is to have an ICTS LIM rewound to the new configuration to minimize costs.) These dimensions are listed in Appendix A.

The normal forces acting between LIM and reaction rail should be kept below 25 kN.

The primary to secondary mechanical clearance will also be identical to the ICTS LIM, which is nominally 11 mm.

2.2 ELECTRICAL CONSTRAINTS

2.2.1 System Voltage

The electrical power delivered to the vehicle will be 3-phase, 60 Hz AC, 1250 V (line to line).

2.2.2 LIM Current

The design limit on current density in the LIM windings is a function of the machines thermal rating and duty cycle. A "people mover" type application will impose a harsher duty cycle than an ICTS application, and hence result in a higher RMS current over an operating cycle for the same peak current loading.

2.2.3 LIM Duty Cycle

Figure 1 shows simplified but representative operating profiles for both ICTS and APM applications. The major differences between profiles result from the lower top speeds and shorter station spacings typical of APM systems. If we assume the same peak current loading for both systems, we find that the RMS current is about 12% lower for the ICTS-type profile. Hence it will be necessary to design the APM LIM to a lower peak conductor current density than the ICTS LIM for the same amount of motor heating.

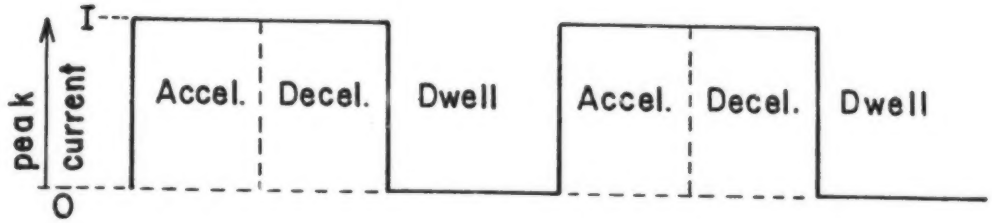
2.3 OPERATIONAL CONSTRAINTS

The speed/thrust characteristic of the LIM must be designed to suit the weight and performance specification of the vehicle. To a large extent, this specification is dependent on the LIM constraints already outlined in the preceeding sections. For example, the voltage and current constraints will impose an output power limit. This in turn will limit the weight and/or performance of the vehicle. The speed/thrust characteristic as presented will represent the design limit as imposed by the electrical and mechanical constraints in addition to the assumed top speed of 14 m/s. This characteristic will suggest a maximum vehicle weight/performance combination.

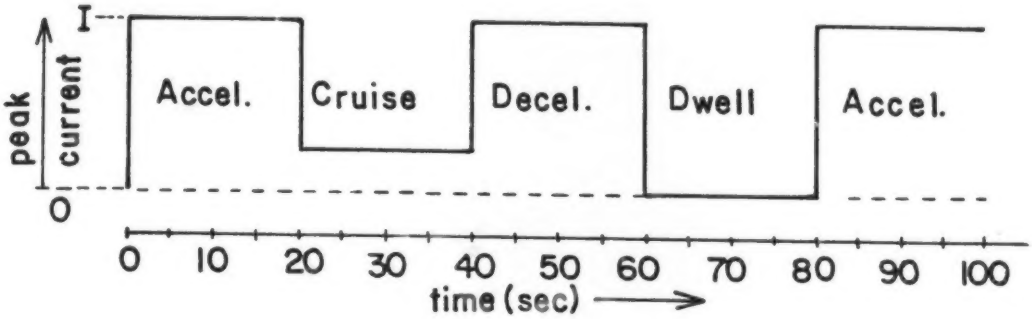
2.3.1 Cruising Speed

The fixed-frequency operating mode implies a pronounced design-sensitivity to the choice of

1) APM PROFILE



2) ICTS PROFILE



$$I_{RMS} = \frac{1}{T} \int_0^T \sqrt{I^2}\, dt$$

FIG. 1 : TYPICAL ROUTE PROFILES

cruising speed. This is because best efficiency is obtained over a relatively narrow speed range as opposed to the ICTS LIM which has a much broader efficiency/speed characteristic.

The cruising speed of 13.3 m/s suggested a 12-pole winding configuration for best efficiency, however further investigation (using the computer model) indicated that a 10-pole winding would provide the best compromise between power factor and efficiency (see Figures 2 and 3), hence this winding was chosen. An additional advantage is the somewhat extended speed range offered by the 10-pole design.

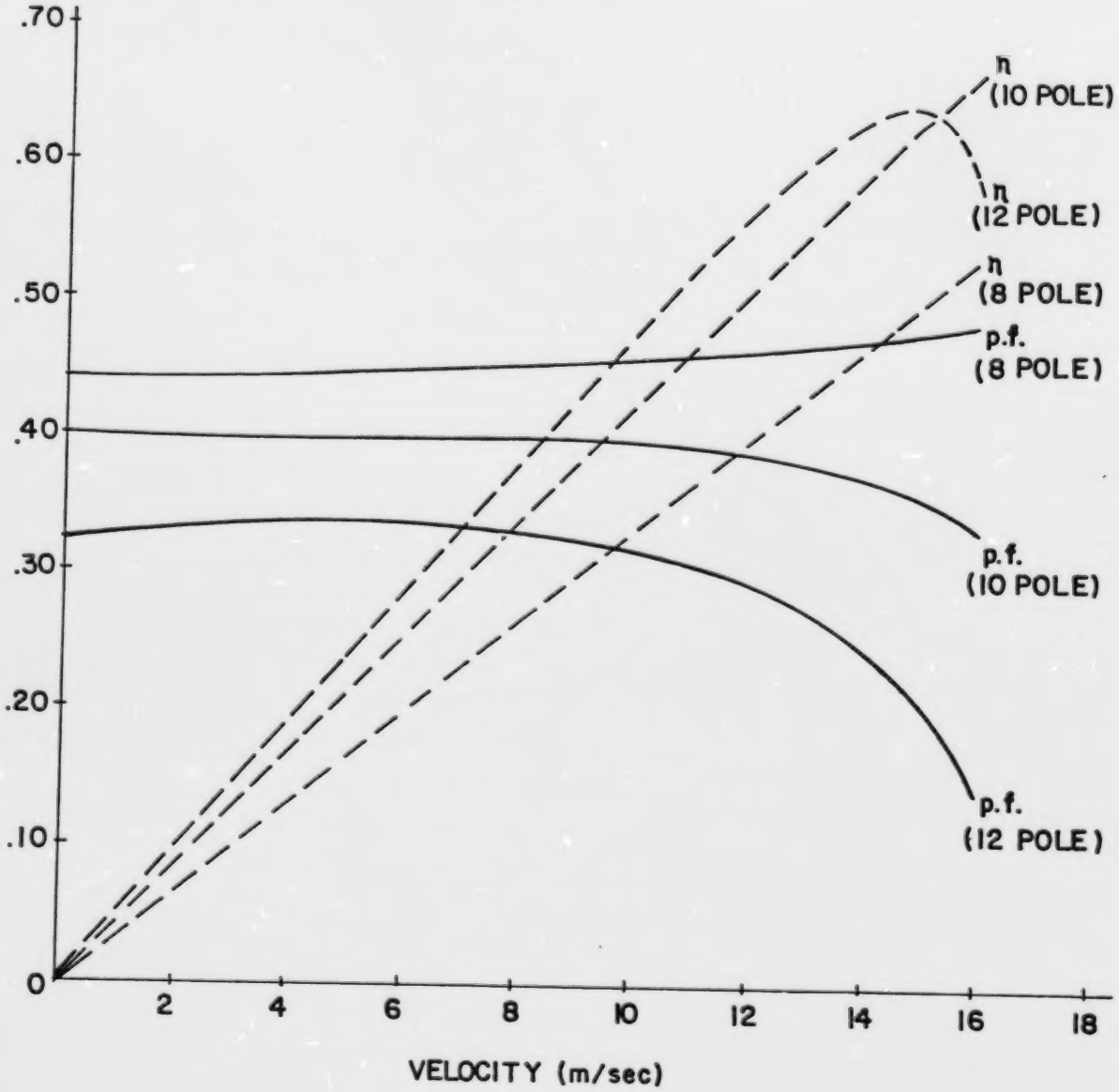


FIG. 2: POWER FACTOR & EFFICIENCY vs VELOCITY FOR 8, 10 AND 12 POLE LIM'S

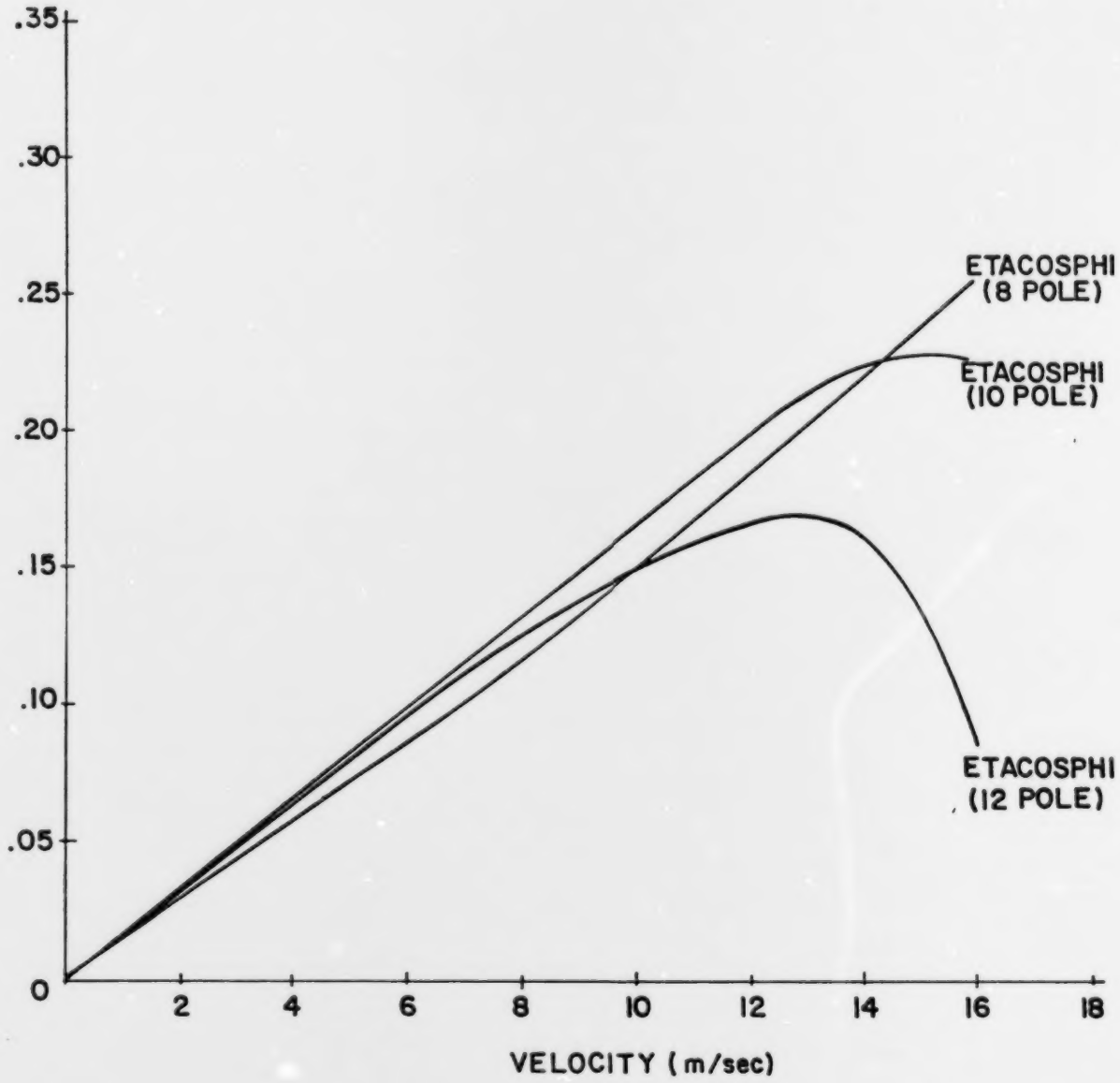


FIG. 3: POWER FACTOR x EFFICIENCY vs VELOCITY FOR 8, 10 AND 12 POLE LIM'S

3.0 LIM DESCRIPTION/COMPARISON

The linear induction motor under consideration is like the ICTS LIM in that it is a single-sided, short-stator configuration. The differences in this LIM, however, are:

1. reaction rail is solid-steel as opposed to aluminum-over-steel,

2. operation is with fixed-frequency (i.e., 60 Hz) excitation rather than variable-frequency excitation, and

3. maximum design speed is 14 m/s while ICTS is 24 m/s.

4.0 LIM MODEL

The computer model used to study the electrical behaviour of the solid steel secondary LIM (S^3 LIM) is a modified version of the model developed by Eastham and Balchin at the University of Bath. The modified version, hereafter referred to as SOLID, can analyze LIM configurations which use non-laminated secondary back iron, or in this case, a solid steel secondary with no conducting top-cap.

The model is based on the solution of field equations in a simplified geometry. The effects of finite machine length and width are handled indirectly.

Input to the model consists of a mechanical specification of the machine and the electrical input characteristics. The assumed machine topology is as follows.

1. Single-sided, short stator.
2. Uniform air-gap.
3. Three-phase, Y-connected, primary winding.
4. Series-connected coils.

The machine length, width, slot size and number, pole pitch, coil pitch, turns per slot, etc., are specified by the user. The user is also required to define the terminal excitation frequency and voltage (or current) as well as the motor linear velocity.

The output of the computer model lists input power, both real and apparent; stator power loss; thrust; normal force; etc., for a given velocity. Field

quantities in the air gap and secondary are also available.

SOLID may be used as a design and analysis tool if its assumptions and limitations are acknowledged. It is intended that the results obtained from SOLID be used to design and specify an appropriate control scheme for the S^3 LIM under consideration. All S^3 LIM performance data shown in this report were generated by SOLID.

4.1 HARMONIC EFFECTS

Wave patterns of the magnetic field in time and space which are non-sinusoidal will influence LIM performance. The harmonic content of such waveforms result in fields which travel at speeds other than the synchronous speed of the fundamental.

The factors which introduce distortions in the "ideal" travelling wave are listed below.

(a) Finite primary winding length.
(b) Primary winding distribution.
(c) Non-sinusoidal excitation source.
(d) Magnetic saturation effects.

The effect of finite winding length is of great importance in a linear machine. SOLID accounts for this effect but ignores the others, which are of secondary importance. When a voltage controller is used to provide excitation to the LIM the effect (c) may become important (particularly in the reduced voltage range).

4.2 PENETRATION EFFECTS

The functions of a LIM secondary are to provide a magnetic path for the flux generated by the primary ampere-turns, and an electric path for the current which the flux induces. (In the ICTS LIM a laminated iron rail provides the magnetic path and an aluminum sheet carries most of the induced current.) When a solid-steel secondary is used, current and flux are distributed in the steel sheet in a somewhat different way. If one were to consider the flux density as a function of depth into the secondary, it would become apparent that a gradient exists. This gradient causes the steel near the surface to be more "saturated" than the deeper material which experiences smaller flux densities. The depth to which this saturated zone extends is a function of the flux density arriving at the secondary surface, and this of course depends on the amount of excitation in the primary. Representative plots of the saturation gradient for two excitation levels are presented in Figure 4. These plots were obtained from SOLID which assumes that the secondary consists of five discrete layers of material, each having a relative permeability corresponding to the average flux density within it.

The current which is induced in the steel secondary tends to be distributed in the saturated zone, i.e., near the surface of the steel sheet. The depth to which the steel is saturated and the current penetrates is often referred to as the "penetration depth".

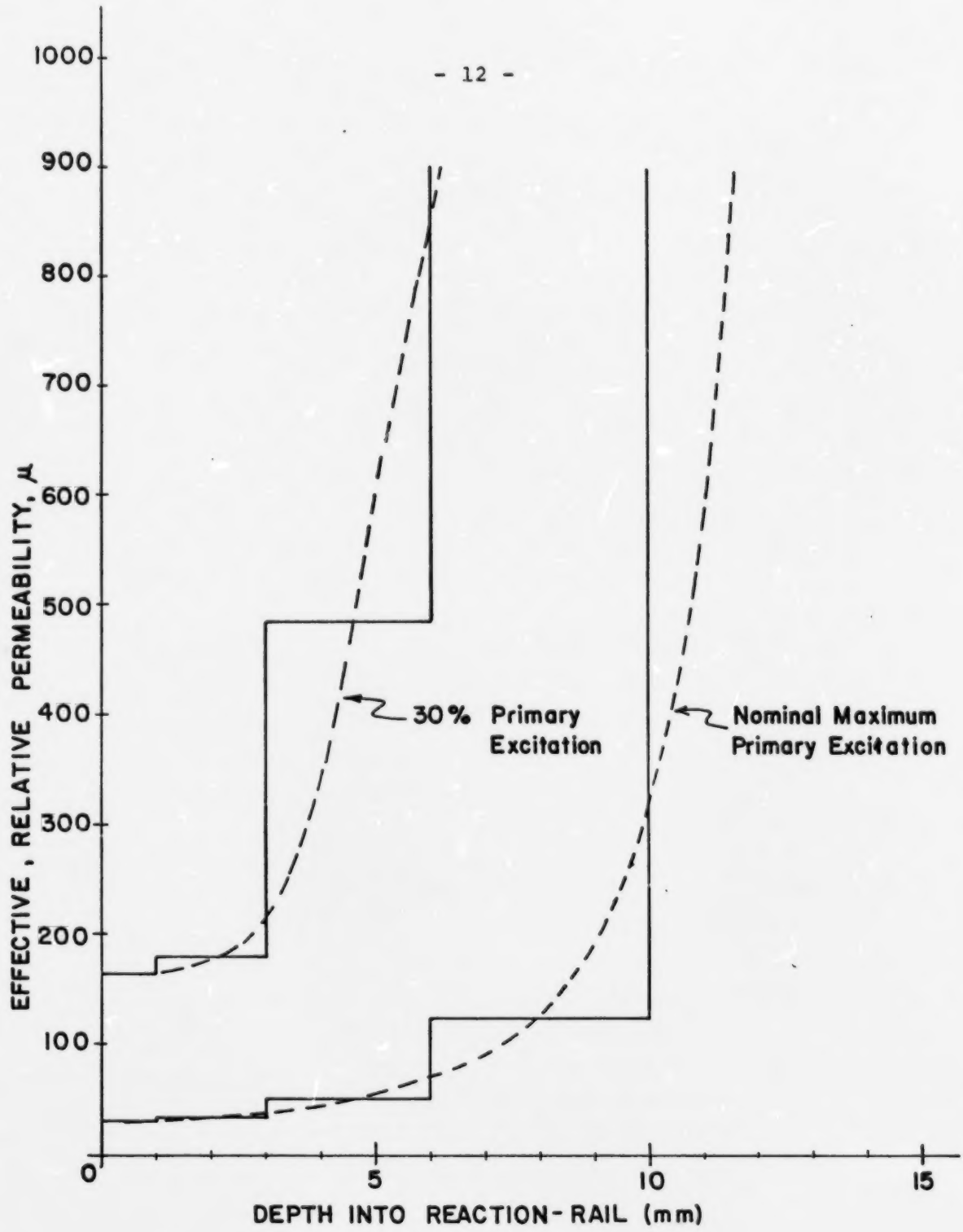


FIG. 4: PENETRATION PROFILES FOR TWO EXCITATION LEVELS

4.3 TRANSVERSE EFFECTS

The current induced in the secondary surface tends to travel in broad loops which correspond roughly to the size of the pole face in the primary stack. The idealized path shape is such that there is only a transverse current component beneath the primary, and that all the turning occurs in the edges of the secondary sheet. The resistance contributed by these edges or "end-bars" is handled in SOLID using the Russell-Norsworthy method.

At lower slip frequencies the idealized current loops are not square as assumed in the model, hence lowering confidence in this regime of results. However, because the LIM under consideration operates at relatively high slip frequencies it is felt that SOLID is adequate. Finite element computer solutions showing the transverse effect at two slip frequencies are shown in Figure 5.

4.4 EXIT-EDGE EFFECTS

The short-stator effect of the LIM can be considered in two parts. One part is the effect of finite winding length, which is accounted for by a harmonic analysis of the step change in current density distribution that occurs at the leading and trailing edges of the machine. (This is covered under "Harmonic Effects"). The other part is the effect of the finite primary core length.

SOLID assumes an infinite core length and then adds an exit-loss correction based on the amount of energy

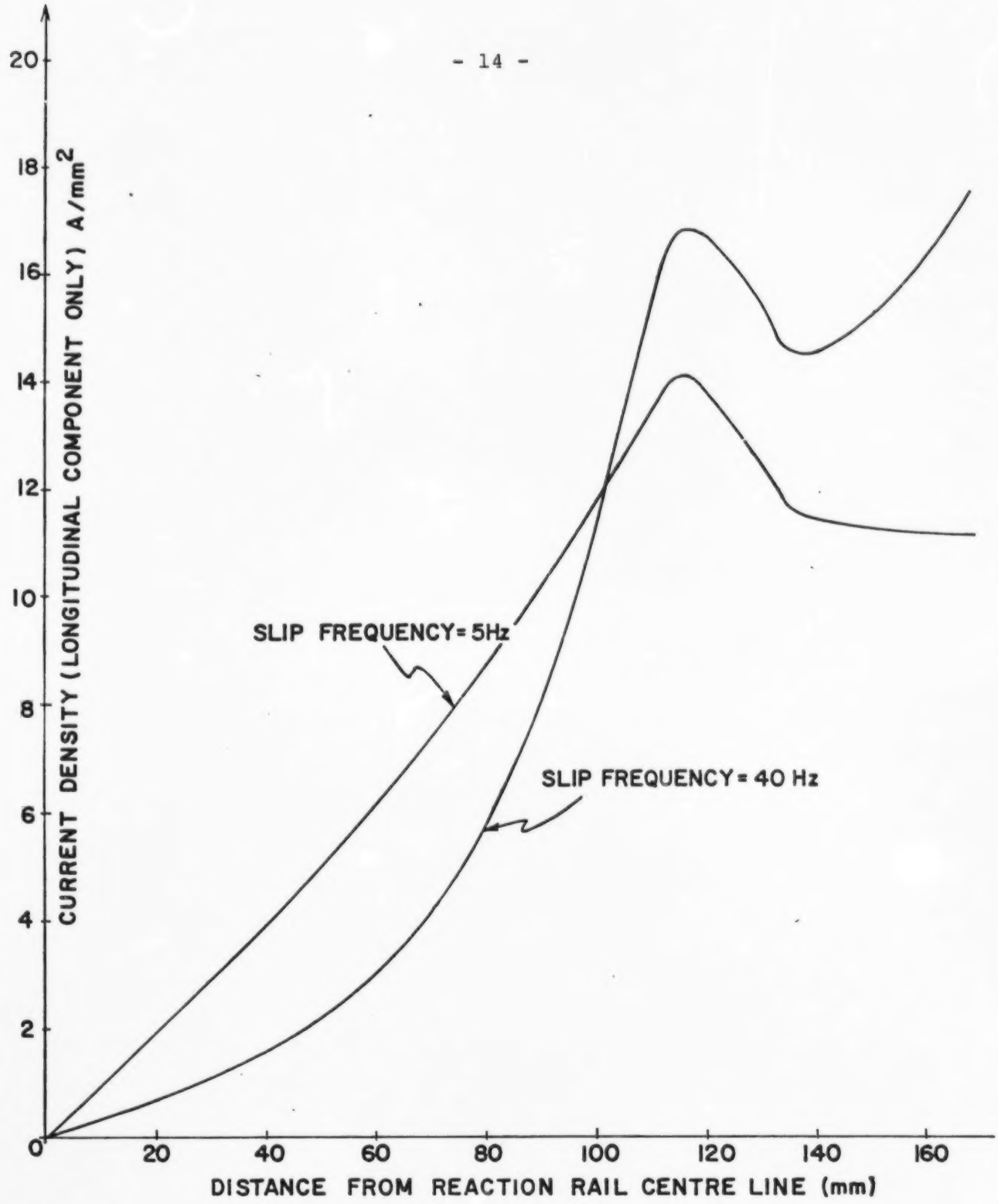


FIG. 5 : LATERAL CURRENT DENSITY PROFILES FOR TWO SLIP FREQUENCIES

dissipated outside the machine length. The short-core effect is generally of less significance than the short winding effect.

4.5 COMPARISONS WITH TEST DATA

The computer model SOLID was checked against test data from the CIGGT/MITRE LIM at Queen's University (Kingston). Good comparison of the model predictions against these test results would give the confidence needed to apply the model as a design tool for a full-scale machine. The test LIM design data appears in App. A. Predicted and measured performance are plotted together in Figure 6.

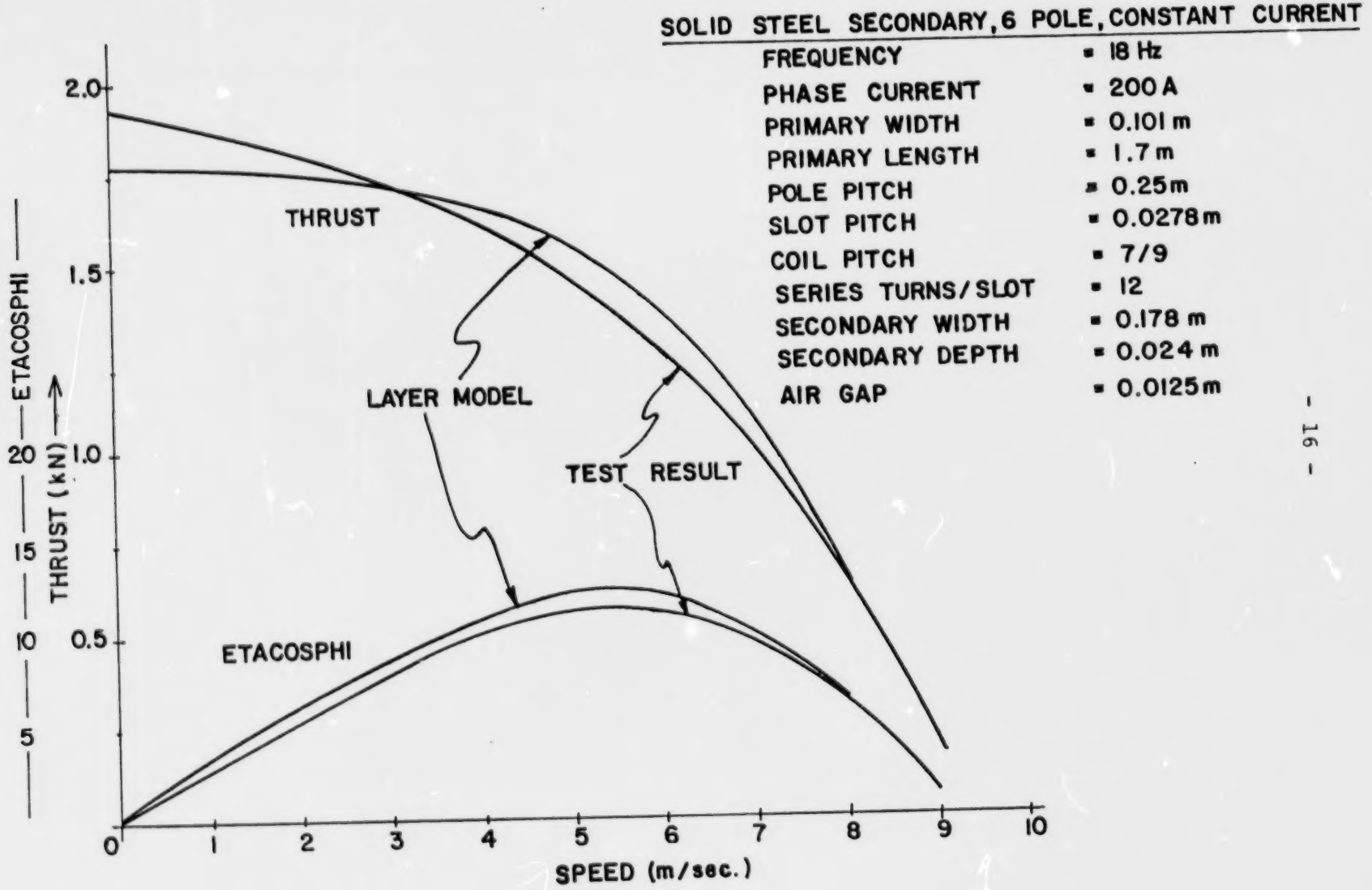

SOLID STEEL SECONDARY, 6 POLE, CONSTANT CURRENT
FREQUENCY = 18 Hz
PHASE CURRENT = 200 A
PRIMARY WIDTH = 0.101 m
PRIMARY LENGTH = 1.7 m
POLE PITCH = 0.25m
SLOT PITCH = 0.0278m
COIL PITCH = 7/9
SERIES TURNS/SLOT = 12
SECONDARY WIDTH = 0.178 m
SECONDARY DEPTH = 0.024 m
AIR GAP = 0.0125m
THRUST
LAYER MODEL
TEST RESULT
ETACOSPHI
THRUST (kN) → 2.0 1.5 1.0 0.5 0
ETACOSPHI → 20 15 10 5
0 1 2 3 4 5 6 7 8 9 10
SPEED (m/sec.)

FIG. 6: PREDICTED and MEASURED LIM PERFORMANCE

5.0 PERFORMANCE PREDICTIONS

5.1 THRUST/SPEED CHARACTERISTICS

Figure 7 shows the thrust profiles which are possible with the proposed propulsion scheme. Curve 2 may be considered an absolute upper limit on motoring thrust, assuming a 290A supply.

Two braking characteristics are shown. Noteworthy is the significantly smaller current required in the D.C. mode, which would then require friction blended with this dynamic braking.

5.2 REAL AND APPARENT POWER

Figure 8 shows the KVA and KW requirement under constant current, voltage limit control for both motoring and plugging modes. Eddy current braking draws zero reactive power from the PCU, and only a small, constant, real power of about 10KW.

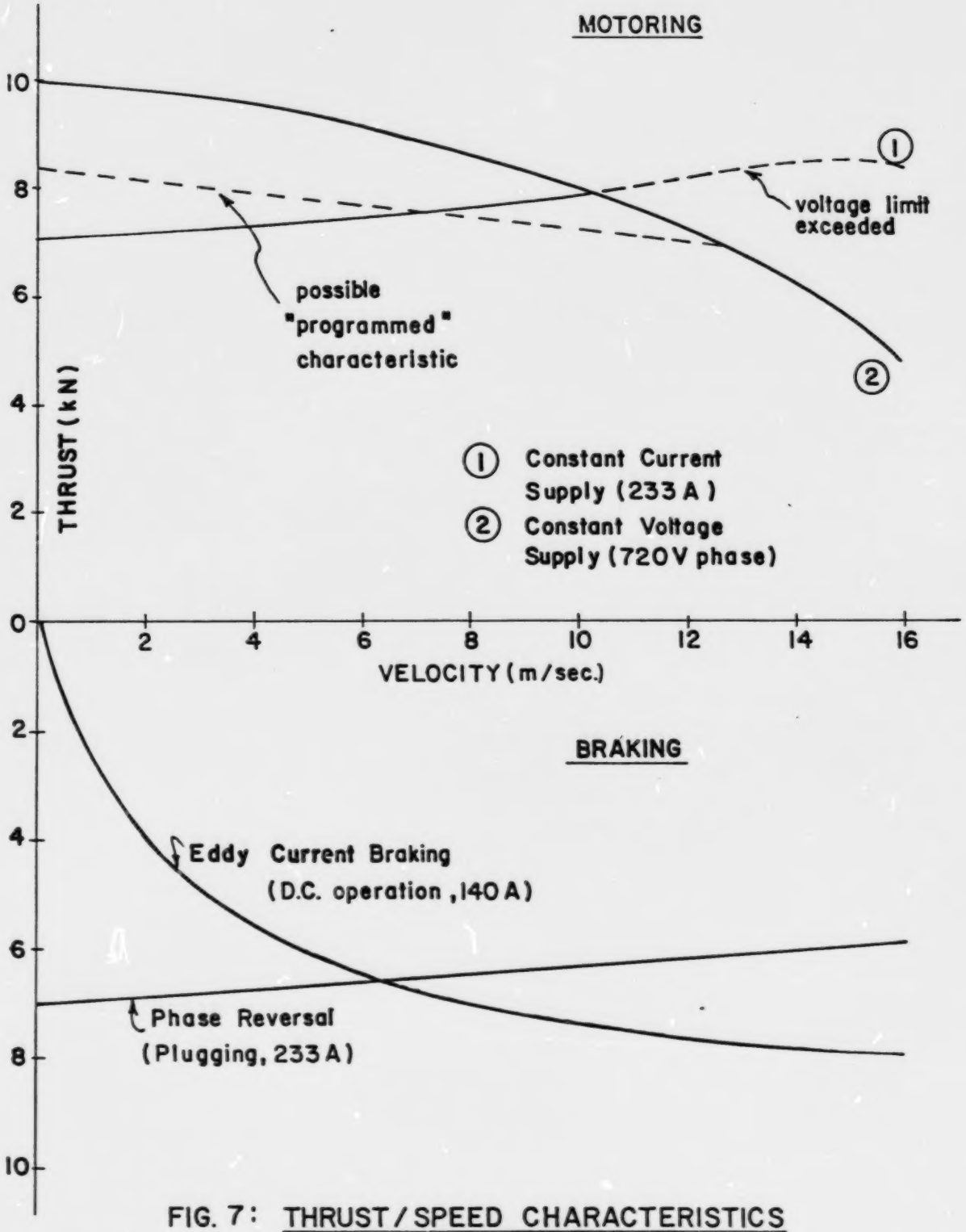


FIG. 7: THRUST/SPEED CHARACTERISTICS FOR 10 POLE LIM (SOLID-STEEL SECONDARY, 60 Hz SUPPLY)

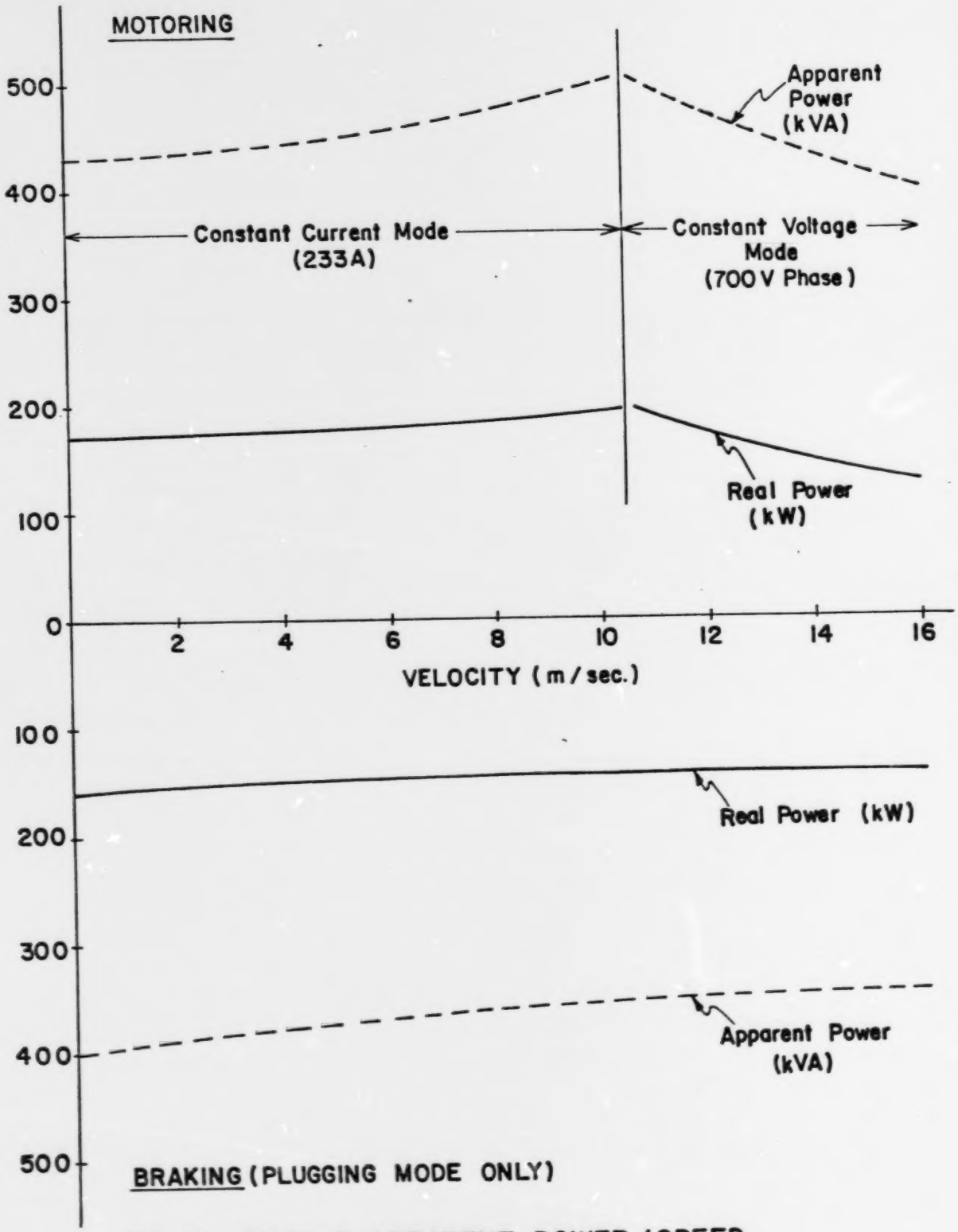


FIG. 8: REAL & APPARENT POWER/SPEED CHARACTERISTICS FOR 10 POLE LIM (SOLID-STEEL SECONDARY, 60 Hz SUPPLY)

6.0 SYSTEM CONSIDERATIONS

6.1 GENERAL

The general system configuration, (section 1) combines with the specific system restraints (section 2) to suggest a particular hardware implementation. However, there are additional design choices to be made with regard to control modes and power factor correction which will influence the final design. These choices lead to cost/performance trade-offs, which will be investigated during actual testing. Some of the possible design choices are presented in this section, with suggestions as to how the test system may be configured so as to assess alternative approaches.

6.2 POWER FACTOR CORRECTION

One of the difficulties of a large air-gap machine is its poor power factor. In the case of a machine with a high pole number, the situation is aggravated. A poor power factor not only imposes higher ratings on the vehicle on-board power conditioning equipment, but also increases the current required from the power distribution system.

Figure 9 indicates the three stages at which power factor correction may be implemented. The "best" strategy may be a combination of these approaches.

Ideally, p.f. correction should be placed closest to the load, however, it will be a practical problem to do this. Placement of capacitor banks on the load

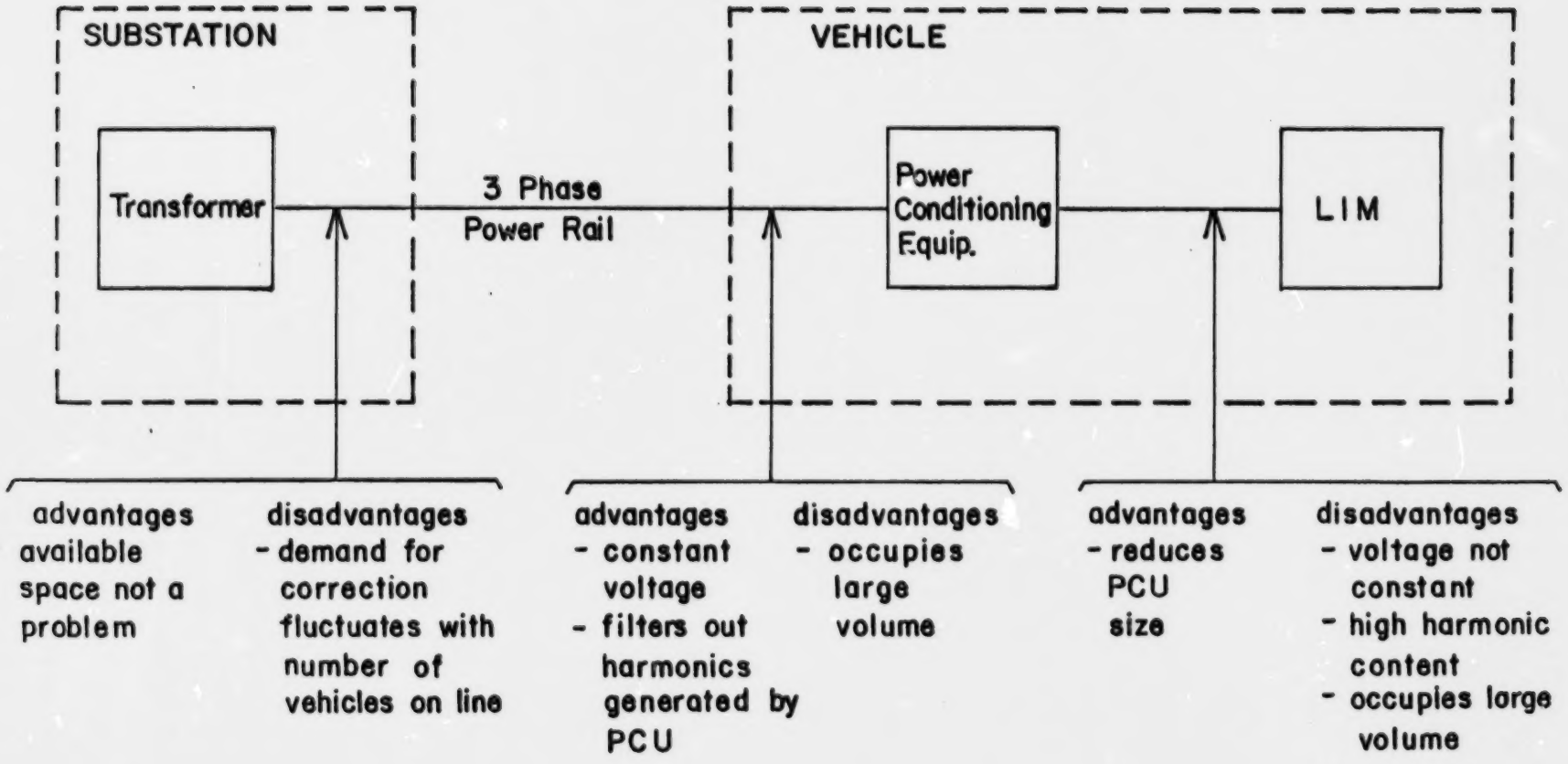


FIG. 9: LOCATIONS FOR POWER FACTOR CORRECTION APPARATUS

side of the controller would require special attention to tuning out the substantial harmonic content of the voltage waveforms. This would be accomplished by introducing inductive elements in series with the capacitance. Placing the capacitance on the line side of the controller is a much simpler problem because the voltage as seen by the capacitor bank is both sinusoidal and essentially constant. The controller would see a poor power factor load, however, and so no saving in PCU rating would be realized.

It is questionable if enough capacitance can be carried on-board the vehicle to completely compensate for the power factor as seen by the supply system, hence it may be necessary to further compensate by installing p.f. correction equipment at the substation. Such equipment may require a control scheme whereby capacitance is switched on or off line according to demand.

The physical volume of power factor correction capacitors is a linear function of their "reactive volt-ampere" capacity. The proposed propulsion system would require approximately 500 kVAR correction per vehicle. The approximate volume displaced by the capacitors can be calculated by using a formula derived from commercial sources.

$$\text{VOLUME } (cm^3) = 364 \times \text{kVAR's} + 250$$

if kVAR's = 500

VOLUME = 182,250 cm^3

This volume does not include spacing, connections and packaging, so another 25% should be added.

6.3 CONTROL OF MOTORING

Figure 7 shows thrust/speed characteristics for both constant voltage and constant current operation. Operating on the constant voltage curve over the duty cycle described in section 2.2.2 would result in motor overheating, however, it serves to denote the upper bound of motor thrust under the given voltage constraint. One possible (and simple) control strategy would be to operate in the constant current mode until reaching the voltage limit, whereafter the controller would operate "full on" up to top speed. Disadvantages to this approach are;

1. The thrust characteristics in constant current mode rises with speed, whereas it would be preferable to have a higher starting thrust which falls with speed. This is a better use of "available thrust" because it minimizes the time spent operating in the inefficient, low speed region.

2. The voltage controller operates better (i.e. with a higher power factor and better waveform) when it is at, or near, full output.

Another possible control strategy which could be an improvement on constant current control would be to use velocity and/or thrust feedback such that a programmed thrust profile is followed (Figure 7). The profile should be chosen to maximize system efficiency within the constraints of RMS current limits, acceleration comfort limits, and so on. Note that the programmed characteristic will also be dependent on vehicle loading to ensure that accleration is regulated.

A "best" motoring control scheme cannot be proposed until overall system requirements have been firmly established, however it is recommended that in the interests of flexibility during testing, the control scheme be designed with speed and thrust feedback as available options.

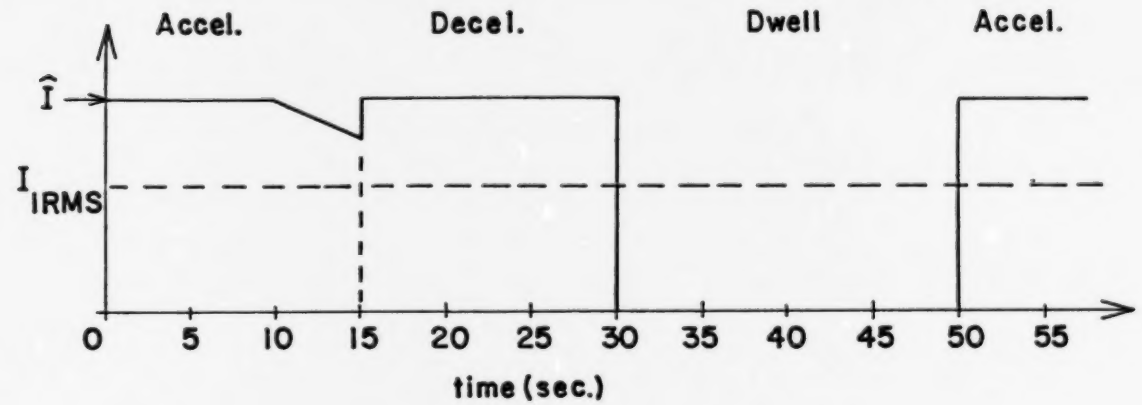
6.4 CONTROL OF BRAKING

Figure 7 indicates two possible thrust/speed profiles which are available in braking. Phase Reversal (or Plugging) is readily achieved and provides braking down to zero speed, however it requires input power of a similar order to that used in motoring. This has the disadvantage of causing higher RMS currents over the operating cycle and reducing system efficiency.

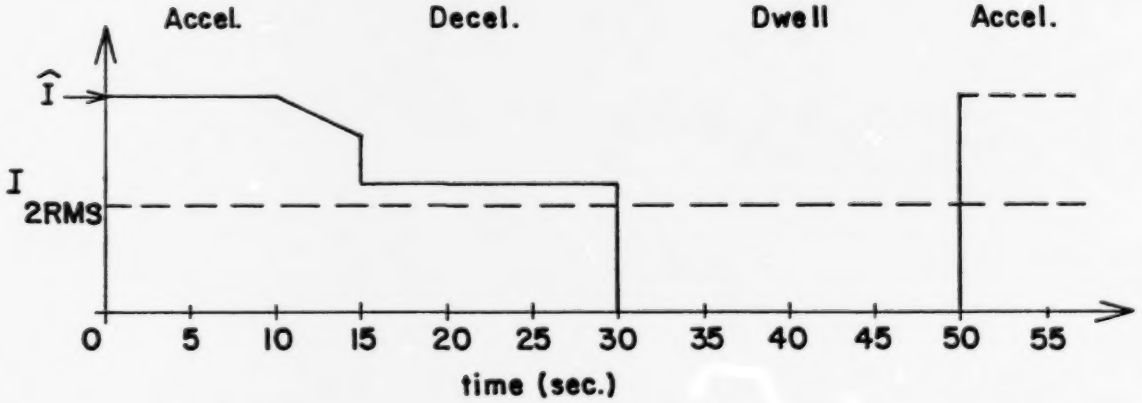
Eddy-current braking requires a reconfiguration of the thyristors into a controlled-rectifier bridge which feed a D.C. current to two of the LIM phases. Also required is the addition of a free-wheeling diode across the LIM phases. D.C. braking requires little input power, but is not effective at low speeds, hence it will be necessary to blend in friction brakes below about 3 meters per second. (D.C. excitation must be reduced at low speeds to avoid excessive normal forces).

From the point of view of system efficiency and motor thermal performance, eddy-current braking is by far the preferred option, but the heavier reliance on friction brakes should be emphasized.

1) DUTY CYCLE USING PLUG-MODE BRAKING



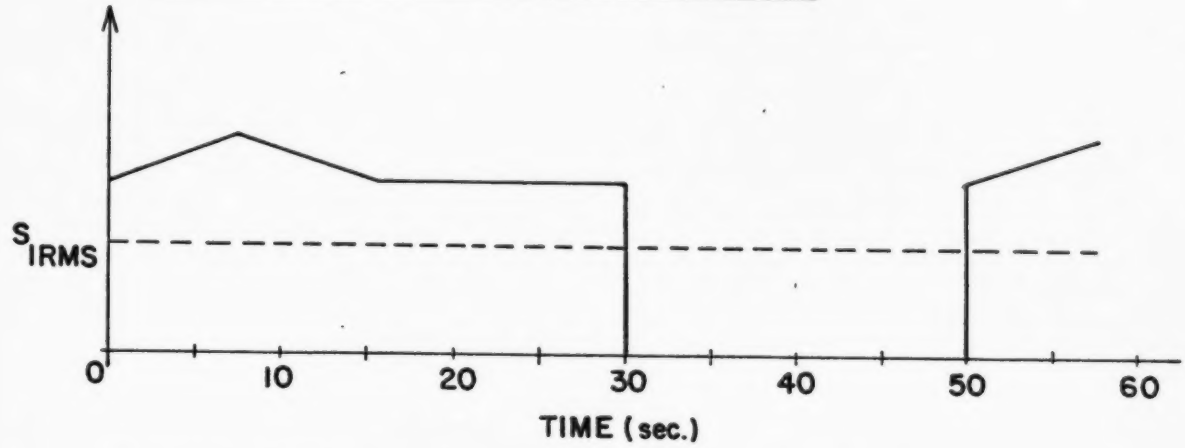
2) DUTY CYCLE USING EDDY-CURRENT BRAKING



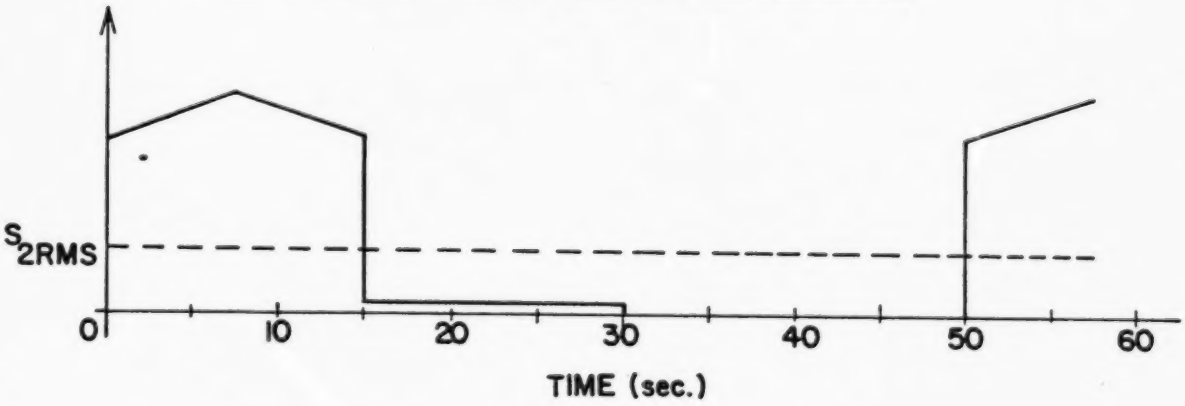
$$\frac{I_{2RMS}}{I_{IRMS}} = 0.8$$

FIG. 10: COMPARISON OF CURRENT DUTY CYCLES FOR A TYPICAL APM PROFILE

1) DUTY CYCLE USING PLUG-MODE BRAKING



2) DUTY CYCLE USING EDDY-CURRENT BRAKING



$$\frac{S_{2RMS}}{S_{1RMS}} = 0.5$$

FIG. 11: APPARENT POWER DUTY CYCLE

6.5 DUTY-CYCLE CONSIDERATIONS

Figures 10 and 11 compare the motor current and KVA for two operating modes on the same route profile. The motor-current duty-cycle will determine primary heating, and the apparent power duty-cycle will determine the power conditioner rating. The reduction in RMS current resulting from employing eddy-current braking is about 20%. In practical terms this means more current is available for producing thrust, and since thrust is proportional to the square of the current, significant gains are possible.

While it is possible to increase motoring current when eddy-current braking is the chosen mode, this does not mean the power-conditioner must have an increased RMS rating. In fact, as Figure 11 shows, the savings in inverter rating are substantial, so even with a 20% increase in motor current the power conditioner will have a smaller rating if eddy-current braking is the chosen scheme.

6.6 SYSTEM VOLTAGE

The system voltage used in all the analyses for this report is 1250 V line to line. Commercially available controllers are generally specified at 600 V maximum however, since higher voltage would exceed the limitations of most thyristors, and series connection of the thyristors would be required. The prototype motor should be wound such that either 600 V or 1250 V operation is possible. This can be accomplished by splitting the coils into two groups of turns which may be externally connected in either series (1250 V) or parallel (600 V) configuration.

REACTION RAIL DEPTH

Figure 4 indicates that the nominal maximum penetration depth is somewhat less than 12 mm, hence a rail thickness much greater than this is (theoretically) a waste of material. The prototype LIM should be tested on a variety of reaction rail thicknesses.

7.0 PROPULSION SYSTEM HARDWARE

The proposed experimental propulsion system is shown in block diagram form in Figure 12. The major components of the system are discussed in the following sections.

7.1 LINEAR MOTOR

The suggested LIM is a rewound ICTS primary structure (see App. A) and a solid steel reaction rail. The reaction rail geometry could best be designed by conducting a series of experiments on the static LIM test rig once the LIM primary has been procured.

7.2 POWER CONDITIONER

It is intended to procure a standard, fully-controlled, three-phase, thyristor bridge with current regulating and gate-drive circuitry. This equipment is shown surrounded by a dashed line in Figure 12. Besides accepting a proportional current demand signal, the power conditioner should accept a logic command which reconfigures the thyristor bridge to provide rectified A.C. (i.e. direct current) to two of the LIM phases. Note that in this mode the current demand signal will control the amount of direct current.

The power conditioner should provide an output which indicates fault status. General PCU specifications are listed in App. B.

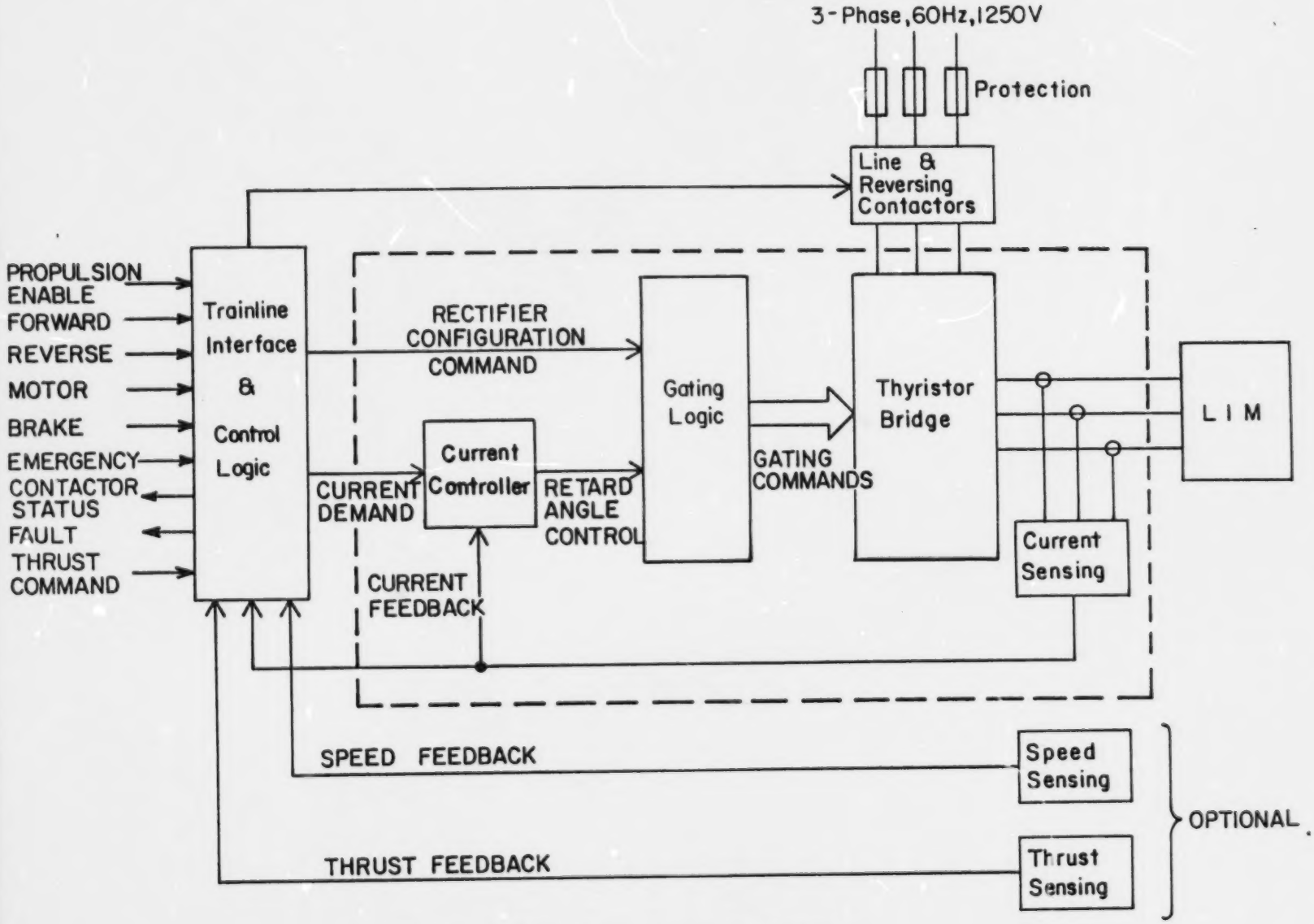


FIG. 12: 60Hz LIM Control Scheme

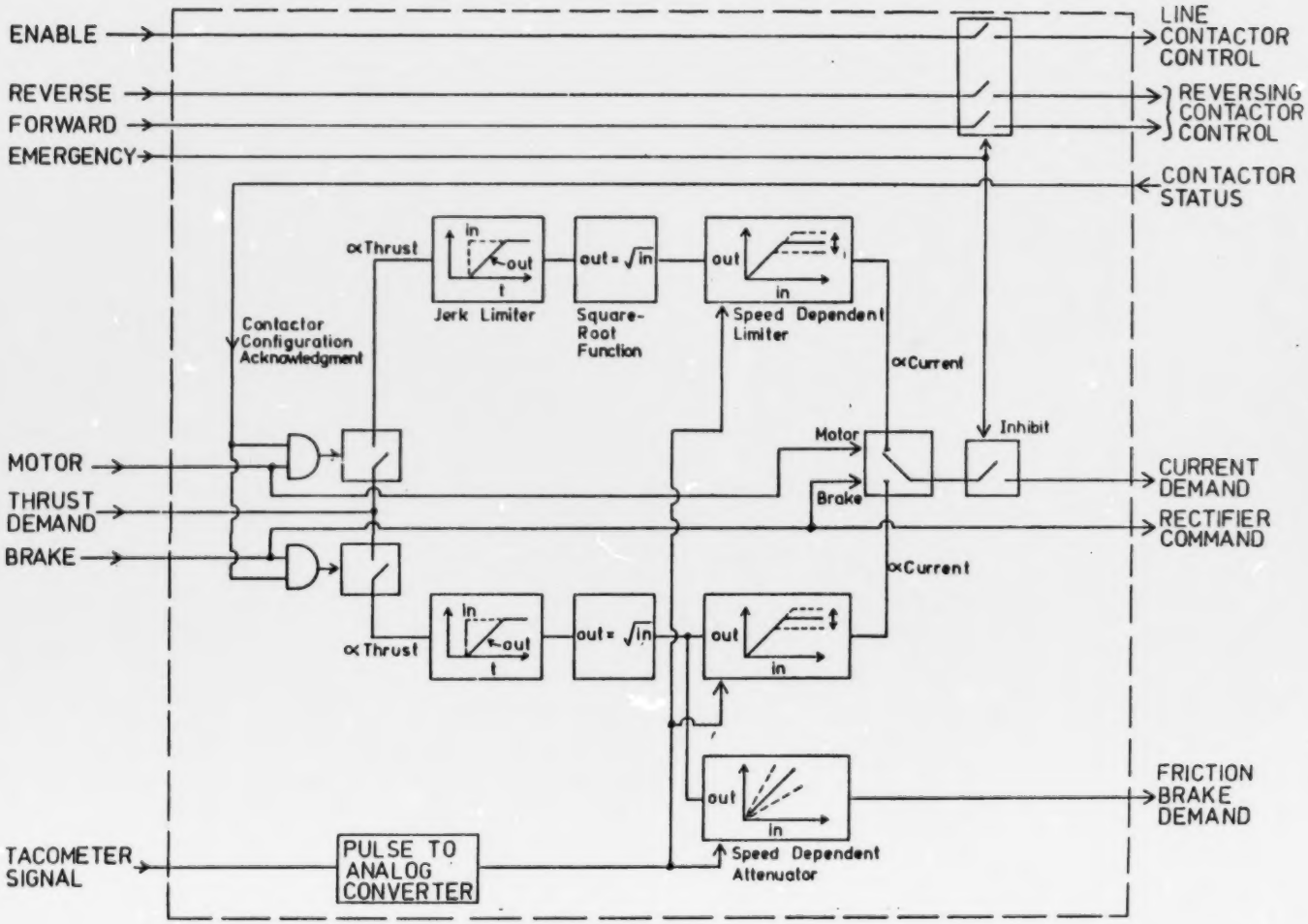


FIG. 12 a Trainline Interface Logic

7.3 LINE AND REVERSING CONTACTORS

These contactors must be able to isolate the propulsion equipment from the line and also to interchange two of the phases. It is not intended that the contactors will normally open or close under load. Commands to the contactors will be generated in the Trainline Interface/Control Logic package.

7.4 TRAINLINE INTERFACE AND CONTROL LOGIC

Figure 12a details the internal functions of the Trainline Interface. Its basic function is to provide command signals to the line/reversing contactors and to the solid-state power controller based on the state of the train control lines.

7.4.1 Propulsion Enable

"Propulsion enable" is a two-state control line which when "high" initiates the closing of the line contactors and connects the input filter section to the three-phase supply.

7.4.2 Reverse/Forward

This pair of control lines sets the contactors such that the phase rotation is appropriate for reverse/forward motion.

7.4.3 Emergency

This control line must be high for propulsion to operate. The loss of this signal will result in 1) the rapid removal of current demand signal

followed by 2) opening of the line and reversing contactors.

7.4.4 Motor/Brake

The "motor" line selects the logic path through which the thrust demand signal is processed before becoming the current demand signal for motoring. The "brake" line selects a separate logic path and also commands the thyristor bridge to configure as a controlled rectifier.

7.4.5 Thrust Demand

The "Thrust Demand" line carries an analog signal (previously decoded from a pulse-width-modulated signal). This analog level is "jerk limited" to prevent excessive rates of change of acceleration/deceleration, "square-rooted" to convert it to a proportional current demand signal, and then limited according to a prescribed current vs. speed envelope to prevent motor overheating. During braking a speed-dependent friction brake demand signal is generated. (Blending of friction braking effort is required at low speeds.)

7.4.6 Contactor Status

This line affirms that the reversing and line contactors have closed, allowing the thrust demand signal to pass into and through the interface logic.

8.0 COST COMPARISON STUDY

8.1 BACKGROUND

The use of commercial frequency, 3 phase power to operate LIM's appears to have inherent cost advantages over the inverter-drive approach. These are primarily due to the simplicity of the power controller and the absence of rectifying bridges in the substations. The great disadvantages of the fixed-frequency approach are that it requires 2.5 to 3 times the peak apparent power, and consumes roughly twice the energy of the variable frequency system.

An overall system cost comparison study was required to assess the two approaches in a particular application. The method chosen to meet this requirement was as follows:

(1) Using the ICTS concept as a baseline, a particular system was defined and divided into its various subsystems (guideway, substation, vehicle, etc.).

(2) A percentage figure was assigned to each subsystem indicating its proportion of the total system cost.

(3) A figure representing the ratio of the cost of the fixed frequency versus the variable frequency approach was assigned to each subsystem.

(4) Using the figures described in (2) and (3) above, a total system cost comparison figure was derived.

8.2 RESULTS

The cost per vehicle estimate (Table 1) indicates that a saving of 15% on total vehicle cost can be realized if the fixed-frequency system is employed. This saving is largely due to the reduction in Power Conditioning Unit cost, and the advantages gained by having a source of 3-phase AC power for vehicle auxilliary equipment such as lights and fans.

The overall system cost estimate (Table 2) shows that despite the savings made in vheicle cost, the fixed-frequency system would actually cost more than a variable-frequency system. The significantly larger kVA requirement, coupled with the poor transmission characteristics of low voltage, high current AC distribution systems, dictated the need for greater substation number and capacity per km.

TABLE 1 "PER VEHICLE" COSTS

SUBSYSTEM	% OF TOTAL VEHICLE COST	COST RATIO FF SYSTEM/ VF SYSTEM
1. Carbody, Trucks & Assembly	39	1.0
2. Air Comfort System	4	0.8
3. Door Control System	2	1.0
4. Friction Brake System	3	0.9
5. SEL Automatic Control	15	1.0
6. Interior Lighting	1	0.6
7. LIM Primaries	7	1.0
8. Power Conditioning	22	0.5
Fuses, Contactors		
Input Filter		
Packaging		
Logic & Sensing		
Power Electronics		
9. Aux. Power Supply	3	0.5
10. Car Wiring & Misc. Electrics	4	0.7

"Per Vehicle" FF/VF ratio = .85

TABLE 2 OVERALL SYSTEM CAPITAL COSTS

SUBSYSTEM	% OF TOTAL COST	COST RATIO FF/VF
1. Guideway Structure & Stations	38	1.0
2. Running Rail	5	1.0
3. Automatic Sensing & Wayside Control	22	1.0
4. Substation	11	1.6
Input Switchgear		
Transformer		
Rectifier		
Output Switchgear		
Auxilliary Equipment		
Building Structure		
5. Power Rail	2	2.0
6. Reaction Rail	5	0.87
7. Vehicle	17	0.85

Overall FF/VF Cost Ratio = 1.054

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The initial analysis has been completed in preparation for the detailed design and development of a "low-cost" propulsion system. The important conclusions which result from the study are:

1. A ten-pole winding configuration will provide the best motor performance over the specified speed range.

2. Power factor correction requirements are large (ratio of reactive to real power is about 2:1).

3. Typical operational requirements would impose lower stator current limits than those of the ICTS motor.

4. Eddy-Current braking is preferrable to Phase-Reversal braking, but friction-braking assistance would then be required.

5. Typical (standstill) available thrust per motor is in the order of 8 kN (20 to 30% lower than ICTS).

6. Peak apparent power requirement per motor is about 500 kVA.

7. Commercial frequency LIM power would offer a saving of about 15% on the cost per vehicle as compared to inverter-powered LIM propulsion.

8. The larger kVA requirements and more frequent substation placement more than offset the "per vehicle" saving such that the overall system costs are greater for the commercial frequency approach.

9.2 RECOMMENDATIONS

The advantages offered by commercial frequency, variable voltage control of LIM propulsion do not justify the extra capital and energy costs incurred when this system is employed in applications such as the Airport People Mover described in this report.

The disadvantages arise from the variable voltage approach for an on-board LIM primary. It is therefore recommended not to proceed with the configuration of on-board LIM primary supplied from a variable voltage controller.

The use of in-track LIM primaries fed from commercial frequency fixed voltage supplies avoids the disadvantages mentioned above and can still achieve the low cost propulsion objective.

APPENDIX A: MOTOR DESIGN DATA

1.	WINDING DATA	
	Pole Pitch	0.1721 m
	Series Turns/Slot/Phase	7
	Slot Pitch	0.0239 m
	Coil Pitch	6/7.2
	Pole Pairs	5
	# of Slots	78
2.	CORE DIMENSIONS	
	Slot Width	0.0156 m
	Tooth Width	0.0083 m
	Slot Depth	0.055 m
	Core Depth Behind Slot	0.0436 m
	Length	1.87 m
	Width	0.216 m
3.	SECONDARY	
	Mech. Clearance to Primary	0.0115 m
	Reaction Rail Depth	0.020 m
	Reaction Rail Width	0.250 m
4.	ELECTRICAL DATA	
	Max. Voltage (line to line)	1250 V RMS
	Nominal Current	233 A RMS
	Connection	3-phase, "Y" connected, no neutral connection

APPENDIX B: POWER CONTROLLER SPECIFICATION AND COMMERCIAL QUOTES

It is intended to use a 3 phase, 60 Hz, solid-state power controller to drive a linear induction motor (LIM) in a prototype transit propulsion system. The prototype system will be used to investigate the potential of commercial frequency control of linear motors as opposed to variable frequency (inverter) control.

The prototype propulsion system design requirements are fairly broad since a number of alternative operational modes need to be studied experimentally. This fact may impose an unusual requirement on the power controller, and it is anticipated by UTDC R&D that a certain amount of design modification on a vendors "standard" controller may be necessary.

This specification outlines the minimum requirement for a power controller. This will allow the vendor to establish a basic unit cost. Thereafter, a set of additional features are listed on a priority basis. UTDC R&D will decide which features it will select based on the per feature cost estimate provided by the vendor. Note that it may not be possible to "modify" a standard unit to provide some of the features. In this case, indicate that a new design is required.

The vendor may assume the following:

(1) Quantity of one only
(2) Isolation and line reversing contactors provided by UTDC R&D
(3) Vehicle-oriented packaging not a consideration for prototype
(4) Auxilliary cooling, if required, will be vendor-supplied

1. MINIMUM REQUIREMENT

• 3 phase, 60 Hz solid-state controller	
• Nominal Input Voltage:	600 V r.m.s. (line to line)
• Input Voltage Variation:	300 to 650 V
• Input Voltage Transients:	TBD
• Input Voltage Phase Imbalance:	TBD
• Input source impedance:	0.7 ohms max
• Nominal Phase Current:	500 A
• Control Mode:	Phase angle delay
• Control Input:	0-10 V analog signal
• Input/Output Relationship:	Output current proportional to control voltage.
• Duty Cycle	See Figs.10 & 11

COST: _____

2. 1250 CAPABILITY

Similar to 1. but with ratings as follows:

• Nominal Input Voltage:	1250 V r.m.s.
• Input Voltage Variation:	600 to 1300 V r.m.s.
• Input Voltage Transients:	TBD
• Nominal Phase Current:	250 A r.m.s.
• Output Control Range:	0 to 1250 V r.m.s.

COST AS ADDED TO 1.: _____

3. RECTIFIER CONFIGURATION

In addition to providing 3 phase A.C. to the LIM, it will be possible to control the bridge such that D.C. (either full-wave or half-wave rectified) is fed through at least two of the windings. Note that an additional component (free-wheeling diode) may need to be added to the power circuit.

COST AS ADDED TO 1.: _____

4. RECTIFIER TO A.C. TRANSITION

If the bridge has been controlled so as to provide D.C. as in 3., it will be possible to return to 3 phase A.C. control with a smooth transition without interrupting power flow to the motor windings.

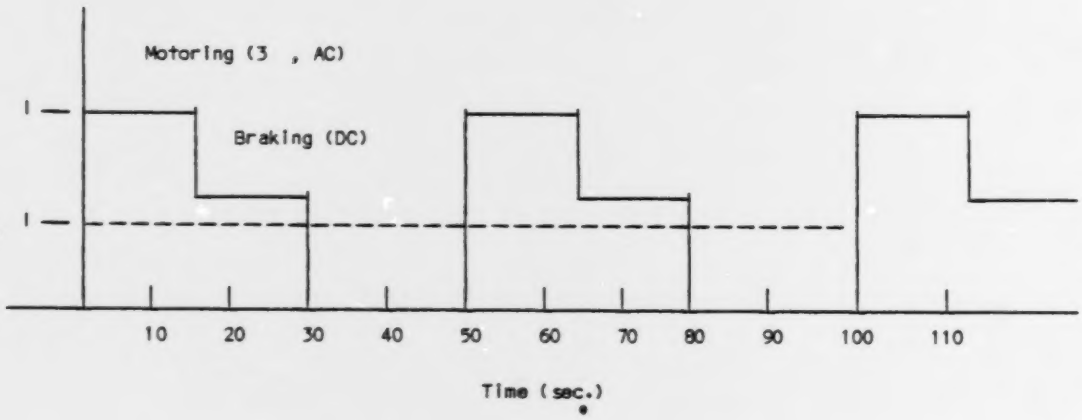
COST AS ADDED TO 1.: _____

5. ALTERNATIVE A.C. CONTROL MODES

In addition to providing phase-angle control of voltage, it will be possible to command integral cycle control or a combination of integral cycle and phase-angle control.

COST AS ADDED TO 1.: _____

TYPICAL SERVICE DUTY CYCLE



(1) 600 V Version

I = 500 A rms

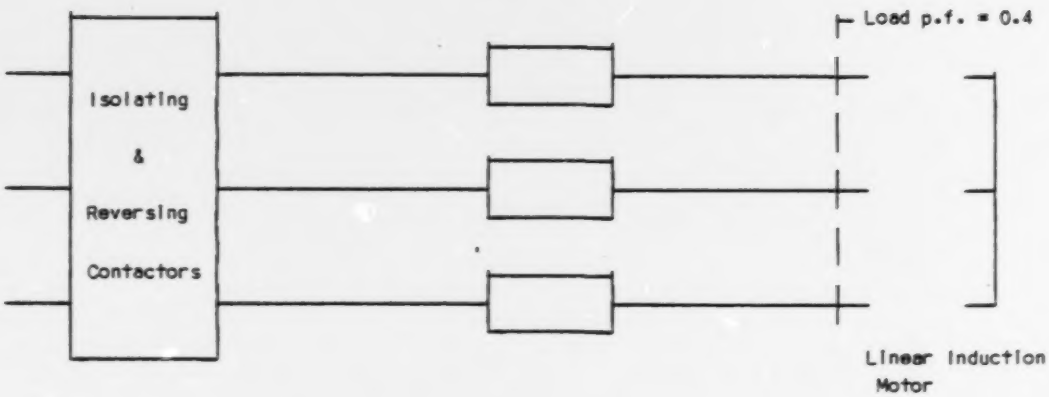
I = 250 A rms

(2) 1250 V Version

I = 250 A rms

I = 125 A rms

POWER CIRCUIT



INTERNATIONAL RECTIFIER CANADA LTD. IOR

HEAD OFFICE: 101 BENTLEY STREET ☐ MARKHAM, ONTARIO L3R 3L1 ☐ TELEPHONE 416-495-1897 ☐ TELEX 06-966650
QUEBEC OFFICE: 280 DORVAL AVE., SUITE 201A ☐ DORVAL, QUEBEC H9S 3H4 ☐ TELEPHONE 514-631-4898 ☐ TELEX 05-821728

October 29, 1982

Metro Canada Limited
UTDC
Kingston,Ont. K7M 6P9

Att.:Mr. O.C. Pennell
Manager, Sub-Systems

Dear Mr. Pennell

We are plesed to submit for your approval, the following budgetary quote :

RE: ENQ 391-1 AC solid state motor controller

Item 1: Minimum system requirement	:	$ 3,400.00 Cnd.TNIP
Item 2: Cost as added to Item 1	:	$ Nil(included in Item 1)
Item 3: Cost as added to Item 1	:	$ 200.00
Item 4: Cost as added to Item 1	:	$ 200.00
Item 5: Cost as added to Item 1	:	$ 200.00

SYSTEM DESRIPTION

DEVICES:	6 700PK300 (700A,3KV SCR) 12 133 type heatsinks 12 pressure clamps Misc. base mtg., etc.
ASSEMBLY DIM:	30"L, 24"W, 24"H
CONTROL:	Microprocessor based, waveform generation and control.
ENCLOSED:	700PK300 data Heatsink databook Standard assemblies databook

Please advise if you require more information.

Yours truly,

Vito Rinaldi,
Applications Eng. Mgr.

Rumble

Rumble Equipment Limited
Les Equipements Rumble Limitée

25 Baywood Road
Rexdale, Ontario M9V 3Y8
(416) 743-8711
Telex 06-527283

2535 Boulevard Cavendish
Montréal, Québec H4B 2Y5
(514) 487-6111
Telex 05-566347

Rexdale, Ontario,
November 1st, 1982.

Metro Canada Limited,
P.O. Box 70,
Station "A",
Kingston, Ontario.
K7M 6P9.

Attention: Mr. O. C. Pennell.

Subject: Enquiry 391-1 A/C Solid State Motor Controller.

Gentlemen:

Further to your letter dated October 12th, 1982, we are pleased to offer for your consideration the following equipment:

1 only, Solid state, 3 phase, 60 Hz adjustable voltage power controller in accordance with your Power controller specification.

The controller will be designed to power a linear induction motor (LIM) applied to a prototype transit propulsion system.

Prices quoted are not to exceed estimates and are net to you F.O.B. Rexdale, Ontario with all taxes extra.

Terms net 30 days.

Delivery 15 to 18 weeks.

Rumble Equipment is a 100% Canadian Company with over 30 years of experience in the supply and manufacture of industrial variable speed drives and systems ranging in size from ¼ HP to thousands of horsepower.

I trust you will find this offer complete.

Yours truly,

RUMBLE EQUIPMENT LIMITED,

A. Archambault/kz.
Attach.

1. MINIMUM REQUIREMENT

• 3 phase, 60 Hz solid-state controller	
• Nominal Input Voltage:	600 V r.m.s. (line to line)
• Input Voltage Variation:	300 to 650 V
• Input Voltage Transients:	TBD
• Input Voltage Phase Imbalance:	TBD
• Input source impedance:	0.7 ohms max
• Nominal Phase Current:	500 A
• Control Mode:	Phase angle delay
• Control Input:	0-10 V analog signal
• Input/Output Relationship:	Output current proportional to control voltage.
• Duty Cycle	See Figs.10 & 11
COST:	$15,000.00.

2. 1250 CAPABILITY

Similar to 1. but with ratings as follows:

• Nominal Input Voltage:	1250 V r.m.s.
• Input Voltage Variation:	600 to 1300 V r.m.s.
• Input Voltage Transients:	TBD
• Nominal Phase Current:	250 A r.m.s.
• Output Control Range:	0 to 1250 V r.m.s.
COST AS ADDED TO 1.:	$12,800.00.

3. RECTIFIER CONFIGURATION

In addition to providing 3 phase A.C. to the LIM, it will be possible to control the bridge such that D.C. (either full wave or half-wave rectified) is fed through at least two of the windings. Note that an additional component (free-wheeling diode) may need to be added to the power circuit.

COST AS ADDED TO 1.: $6,000.00.

4. RECTIFIER TO A.C. TRANSITION

If the bridge has been controlled so as to provide D.C. as in 3., it will be possible to return to 3 phase A.C. control with a smooth transition without interrupting power flow to the motor windings.

COST AS ADDED TO 1.: $15,000.00.

5. ALTERNATIVE A.C. CONTROL MODES

In addition to providing phase-angle control of voltage, it will be possible to command integral cycle control or a combination of integral cycle and phase-angle control.

COST AS ADDED TO 1.: $28,000.00.

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